

EXPLOSIVE

3D printing could revolutionize the high-

THREE-DIMENSIONAL PRINTING IS BLOWING UP. From the obvious—hand tools and chess pieces—to the less obvious—body parts and shelf-stable food—just about every item imaginable is being subjected to the two-step process of digitization and fabrication that is 3D printing.

One of the factors fueling the excitement is the ease with which 3D printing can be used to build items with hollow internal spaces—that is, to build something around nothing. This task is always hard and often impossible by conventional manufacturing methods, which usually involve creating an item by removing material from a larger mass and so are referred to as subtractive manufacturing methods. A hollow ball, for example, might be crafted in one of two subtractive ways: by making a hole in a solid sphere and reaching inside to scrape out the center, then covering the hole; or by casting two separate hemispheres, sticking the halves together, and obscuring the seam. A 3D printer, on the other hand, manufactures additively by stacking thin layers on top of one another until a 3D object is formed. So it could whip out a hollow ball in no time without hidden holes or seams.

Los Alamos chemist Alex Mueller leads a team that is using 3D printing to create next-generation high explosives. Since the First World War, scientists have known that the behavior of trinitrotoluene (TNT) can be altered by the addition of certain materials, such as detergent or sand. Infusing TNT with bubbles or grains rendered it more sensitive


and easier to detonate—but no one knew why, so TNT was (and still is) difficult to control. The Los Alamos team is working to understand not only what goes on inside an

One thing making 3D printing so popular is its ability to build items with hollow internal spaces.

explosive during detonation but also how to control and tailor it through manipulation of its internal hollow spaces and microstructures. And a 3D printer is the ideal tool for the job.

Hot spots and not spots

Explosives are categorized as either low or high, depending on whether they burn (low) or detonate (high). Detonation involves an explosive shock front traveling through the material faster than sound can travel through it, while burning is entirely subsonic. In a conventional high explosive (CHE), such as TNT, the chemical reactions and supersonic shock front are relatively easy to initiate, and therefore CHEs are not immune to accidental detonation. Indeed, fires, accidents, or other munitions can cause a CHE to detonate



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-explosives industry.

unintentionally. To reduce the risk of accidental detonation, Los Alamos supports the development of insensitive high explosives (IHEs), which are insensitive to incidental detonation. An IHE can be dropped, run over, hit with a hammer, or engulfed in flames, and it won't detonate—but it is also more difficult to detonate intentionally and can lack the power of a CHE.

So the choice would seem to be between the efficacy of CHEs and the safety of IHEs. But there might be a way to have both. The approach the Los Alamos team is taking is a sophisticated step-up from mixing soap into TNT. When inclusions such as air bubbles are introduced into a material, that material can either allow the bubbles to escape upon compression (like a sponge), or it can trap the air inside (like neoprene). High explosives can do the latter. So when the material is subjected to a shock wave, the voids (bubbles) inside collapse, which causes a rapid heating of the explosive material due to its uneven flow into or around the voids, and results in tiny points of intense heat referred to as hot spots. Up until now, high-explosive shock sensitivity—the intensity of shock required to initiate detonation—has been largely a matter of how hot spots interact at microscopic scales. These interactions can make a high explosive either very easy or very difficult to detonate. But the Los Alamos team is after something more than crude control of an on-off switch. It wants the best of both worlds: a tailorable explosive with a sophisticated arrangement of hot spots that allows for the energy release to be “tuned” while maintaining insensitivity for safety.

Printing pays off

Mueller came to Los Alamos as a postdoctoral researcher to develop materials for new LEDs (light emitting diodes). Several years ago, he started incorporating 3D printing into his work for a variety of purposes. Then, after brainstorming with some colleagues who were having trouble making off-the-shelf printers do their scientific bidding, they decided to hack one, reprogram it, and adapt it for new types of projects. That's when they began thinking about explosives and the revolution that 3D printing might bring.

“Because it's a new technology, there's this temptation to try and do everything with 3D printing,” Mueller explains, “but new technology isn't necessarily always better than the old way. Using a power drill as a hammer, just because it's fancier, isn't going to be better than using a hammer as a hammer. But in this case, the new technology has made the difference from impossible to possible.”

Even in the 2D world, before printing comes a lot of theory and design. The team's theoreticians, led by Brad Clements, produce exacting calculations that the experimental team then tests in the lab. Through intense iteration between theory and experimentation, the team has so far zeroed in on some key points.

During detonation, a chemical reaction zone (CRZ) races immediately behind the supersonic shock wave; the shock-compressed voids in the CRZ generate hot spots and in turn

initiate the chemical burn reaction. Because a shock front will move through different materials at different speeds, the type, size, and distribution of hot spots (collectively referred to as the hot-spot profile) can change the size and speed of the CRZ as it travels through the material—this affects the strength of the subsequent blast.

Dana Dattelbaum, a Los Alamos detonation expert, led a series of experiments that tested different ways of seeding hot spots: solid or hollow glass spheres were suspended at different

During detonation, a supersonic shock wave races through the explosive.

densities in a gel-like liquid explosive. The physical properties of the detonation were measured and compared to reveal how, precisely, different hot-spot profiles affect the shock sensitivity, shock initiation mechanism, and CRZ. This information can help the team determine what hot-spot profile they ought to give their experimental 3D-printed explosive material. “The ability to tailor sensitivity and the resultant energy release in the chemical reaction zone would be a holy grail in detonation-physics research,” Dattelbaum says. “Control and manipulation of structures at the microscopic scales through 3D printing is an exciting step toward achieving these goals.”

Part of what gives CHEs greater explosive power over IHEs is the way energy is released behind the shock front. In a CHE, the explosive detonates or reacts promptly while in an IHE the energy release is slower, which affects how the detonation propagates. This difference is largely explained at the mesoscale—larger than atomic scale but smaller than what can be seen with the naked eye. With archaic production methods, which usually involve taking a putty-like substance and casting or pressing it into the desired shape, the crystal structure at the

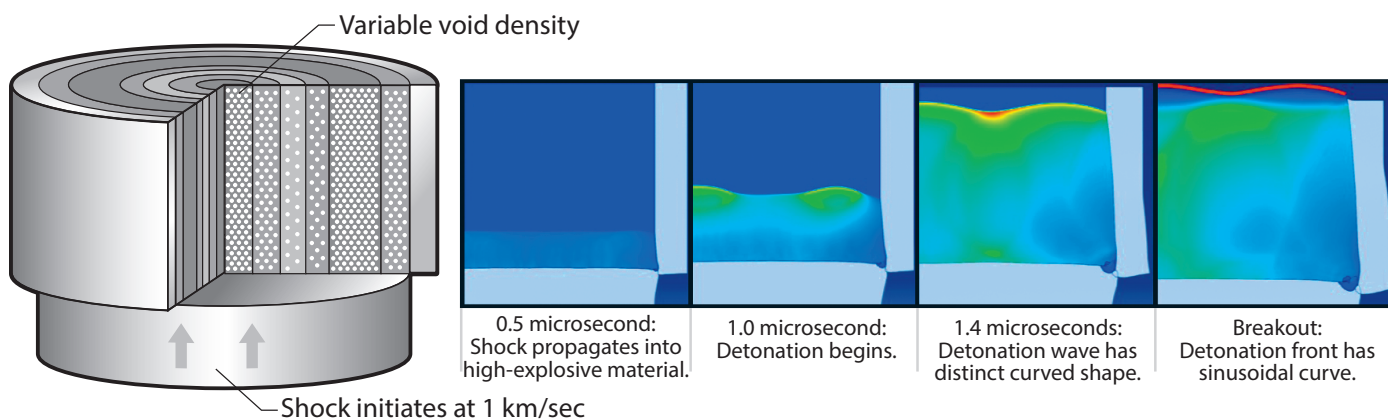
mesoscale is a mess. Different discrete mesoscale regions within the material have their atomic structures aligned every which way, with no cohesion or regularity. So each region has to be initiated on its own in a rapid chain reaction. For CHEs, the chain reaction is fast and usually complete—every region initiates and contributes energy to the total explosive output. But for IHEs, each mesoscale region is just as hard as the last to initiate and some just don’t go. These regions are called dead zones and are basically wasted material. In short, IHEs are inefficient.

Structures at the mesoscale are highly heterogeneous and famously difficult to manipulate. But thanks to 3D-printing technology, the door to this difficult-to-target, difficult-to-manipulate, difficult-to-measure, nebulous no-man’s land has swung open. The Los Alamos team creates each mesoscale layer in a 3D-printed high explosive first by using a fine-featured nozzle to trace out the voids, then a larger-apertured nozzle to fill in the area around the voids. Each layer contains a precise number of voids arranged in the optimal hot-spot profile. No more variable regions means better reliability. No more unpredictability means better safety.

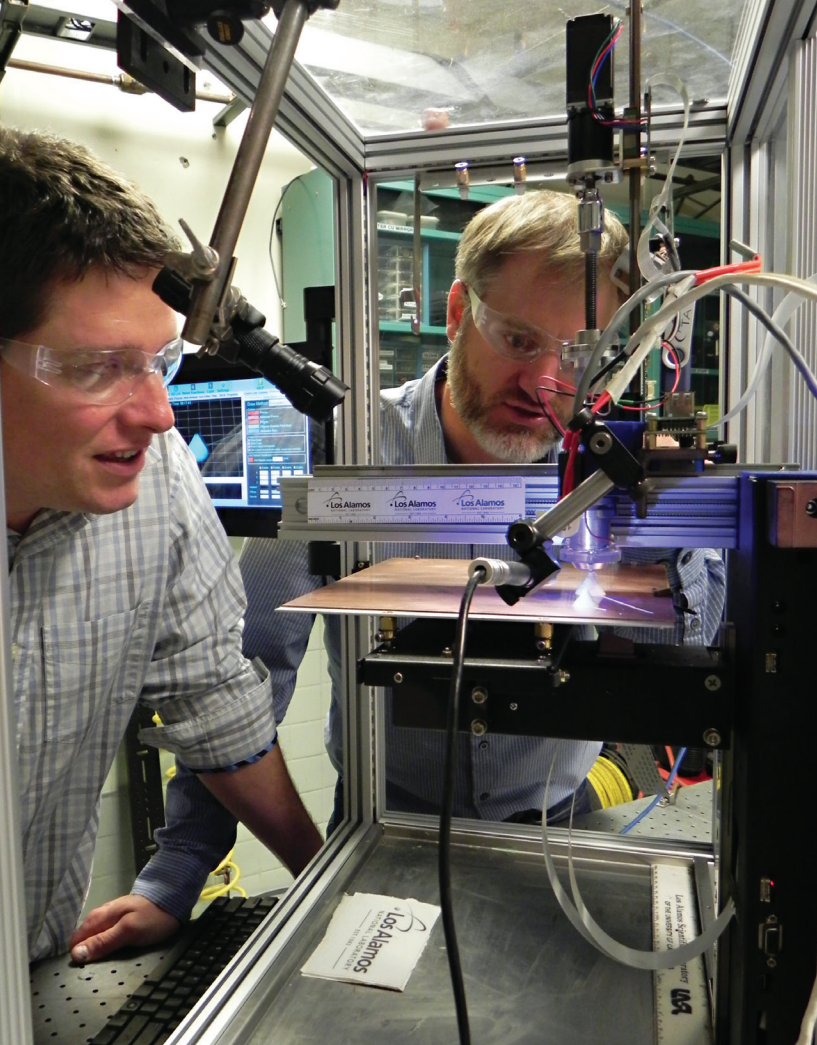
Booming industry

It’s not just the manufacturing process that the 3D-printing team is revolutionizing. It’s the materials themselves. It might seem that the best way to build a next-generation explosive with high safety and high performance would be to modify an existing material—either increase the safety of a CHE or increase the performance of an IHE. But that’s not what these scientists are up to. They are developing entirely new materials. Bryce Tappan, who leads the chemical formulation and synthesis effort on the project, says this is part of what makes their work special. It’s not a one-off or an upgrade—it’s something brand new. And it’s flourishing rapidly.

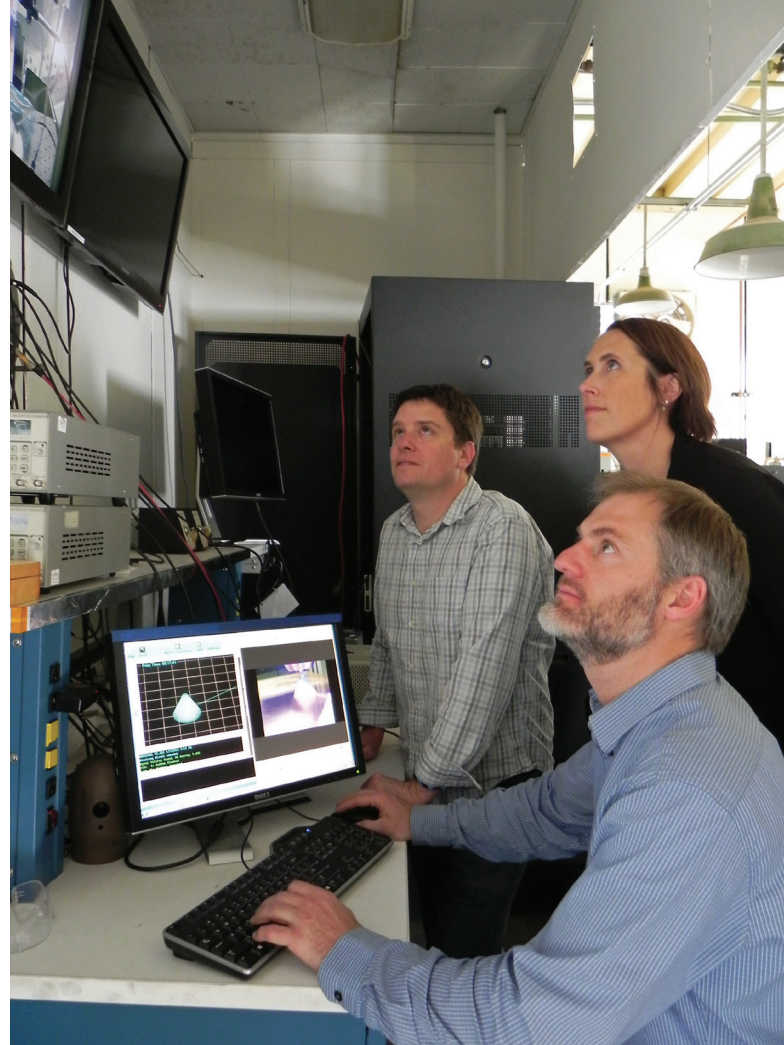
Right now the team is using two kinds of additive manufacturing—both of which can deposit layers at the desired mesoscale size. In fused-deposition modeling, the material is



Los Alamos scientists demonstrated, theoretically, how to exert unprecedented control over the behavior of an explosive by manipulating its microstructure. In this proof-of-concept simulation, they tailored the detonation front at breakout—the point at which an explosive produces an actual blast—by grading the sensitivity of the explosive material. A cylinder of high-explosive material constructed with radially varying void densities was subjected to a shock, initiated by hitting the bottom of the cylinder with a shock plate traveling at one kilometer per second. The higher the void density, the faster the shockwave propagates, and as a result, the detonation front at breakout displayed a distinct sinusoidal shape that confirmed the new level of control.



Los Alamos chemists Bryce Tappan and Alex Mueller watch as their one-of-a-kind 3D printer produces a little cone of mock explosive material. The process allows custom tailoring of internal structures that was not previously possible.



Some of the leaders of the 3D-printed explosives project watch from the safety of a control room as they print a little cone of customized explosive material (left to right: Bryce Tappan, Alex Mueller, and Dana Dattelbaum).

first melted and then extruded in thin layers that solidify upon cooling before the next layer is added, much like a hot glue gun. In optically cured additive manufacturing, ultraviolet light is used to cure each layer as it's deposited, taking it from liquid to solid in mere seconds, just like composite-resin dental fillings.

The team is revolutionizing both the manufacturing process and the explosive materials.

Los Alamos has already developed novel explosives from blended materials, and although the 3D-printing team has the capability in place to work with such mixed materials, the scientists are not yet ready to move on from single materials with air-bubble voids. Mueller is adamant about putting first things first. They're working out the physics, the chemistry, the computation, and the models. But because of the existing

knowledge base at the Lab and the readily available resources, facilities, and unparalleled expertise, they are uniquely situated at the forefront of the high-explosive additive manufacturing field.

"Some people think we're just up here building new dangerous and terrifying things," says Mueller, "but really what we're trying to do is make everything a whole lot safer." **LRD**

—Eleanor Hutterer

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- **Materials at the mesoscale**
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